UCRL-87288
PREPRINT

CHARGED PARTICLE BEAM WEAPONS

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This paper was presented as part of the Air Force sponsored Pulsed Power Lecture Series. The lecture was given at Wright-Patterson AFB and at Kirtland AFB on November 5 and 6, 1981 respectively.

December 9, 1981

Lawrence Livermore Laboratory

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I. ABSTRACT

Charged particle beams represent an application of pulsed power technology that promises a potential military breakthrough. Their future use as weapons depends on the feasibility of propagating intense, self-focused beams through the atmosphere. The present DARPA Particle Beam Technology program is aimed at answering these feasibility issues with the Advanced Test Accelerator facility at LLNL.

Even with positive test results from ATA, weaponization of particle beams will remain many years in the future. Part II. of this paper gives a broad brush picture of a particle beam weapon system to place the present research program in a weapon development context. It also presents an example of the potential high payoff of the technology.

*The Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy under contract number W-7405-Eng-48.

This work is performed by LLNL for the Department of Defense under DARPA (DoD) ARPA Order 3718, Amendment 41, monitored by NSWC under Contract No. N60921-81-LT-W0043, and DARPA Order No. 4395 A#1.

This lecture was requested by the Pulsed Power Education Panel and presented as part of the Air Force sponsored Pulsed Power Lecture Series. The lecture was given at the AF Institute of Technology at Wright-Patterson AFB and at the Air Force Weapons Laboratory at Kirtland AFB on November 5 and 6, 1981 respectively.

Part III. is an overview of the propagation physics which is the main area under investigation in the DARPA program. In an appendix, the ATA facility and its rationale are described.

II. CHARGED PARTICLE BEAM WEAPONS IN PERSPECTIVE

A. Generic Advantages

We may define a charged particle beam (CPB) weapon as one in which energy is delivered from the weapon to the target by means of an intense, small-solid-angle beam of particles traveling at very nearly the speed of light (c). Such weapons will in general be complex systems with many technologically diverse subsystems. Issues of feasibility aside, it will be when the unique generic characteristics of CPB weapons give an important "battle" advantage that they should be deployed in lieu of more conventional, often much simpler advanced weapons. Indeed, CPB weapons may have to do something that conventional weapons cannot do. Moreover, the conflict between CPB weapons and conventional ordnance will not be just a figurative one; as complex and costly systems they must be protected from or be relatively immune to saturation attacks by inexpensive, "technologically inferior" weapons.

The most apparent generic characteristics of beam weapons are readily inferred from their principal features: 1) Energy reaches the target extremely quickly, with a velocity at or near the speed of light; 2) the angular divergence is small; 3) the beam has a high energy-to-momentum ratio.

From these features we infer the following characteristics. First, energy is delivered from the weapon to the target in a time short compared with the available engagement time. This characteristic is often called "zero time of flight" even though the times may actually be as great as thousandths of a second.

A second characteristic of CPB weapons is a very rapid rate of fire, usually in excess of several bolts per second. Rates can be orders of magnitude higher than this for the beam-generating device (accelerator) itself, and the operational limit may derive from non-device subsystems--for example, slewing-speed limitations. In practice, high rates of fire and small delivery times allow for multiple shots at the target--shoot, look, shoot. This feature may not be a luxury for proposed systems, which do not necessarily hit the target with the first shot.

Almost a corollary to rapid rate of fire is the very large--if not unlimited--number of shots available to fire. In turn, the cost per shot is often small, a fact that facilitates operator training and device testing. A further consequence is the need for rapid update of fire control.

As a consequence of the relatively small angular divergence of the energy pulse, the requisite total energy from the device to produce a given degree of damage is reduced with respect to a weapon with energy output over 4π. Additionally, collateral effects are also reduced.

The non-nuclear nature of CPB weapons is a tactical battlefield advantage and a research and development advantage with respect to the present SALT and nuclear test treaty environments. Compared with nuclear weapons in a (ballistic missile defense) role, CPB weapons do not suffer from self-induced blindness or blackout.

The very nature of CPB weapons as a complex of diverse high-technology subsystems could provide an advantage to the U.S. vis-a-vis other countries in the actual construction of such a weapon. Because such an advantage with respect to the Soviet Union is probably not large, the cost, complexity and long development times for these weapons demand a strong long-term commitment on a large scale if the advantage is not to be lost.

The complex high technology of CPB weapons is also a source of a number of the principal generic disadvantages of many CPB concepts--namely, large weight, volume, and power requirements. In addition, this high-technology system must evolve from the laboratory stage to one in which it is operable by normal battlefield personnel. The operability requirements are further complicated by safety requirements at the weapon site, especially those relating to radiation levels in the vicinity of the weapon.

A number of CPB concepts suffer from large "missing links" in relevant science and technology. Crucial scientific demonstrations of essential links such as beam propagation are often missing. All in all, the high potential payoffs are presently accompanied by high risk in many cases.

Table I summarizes the generic advantages and disadvantages we have described for particle beam weapons.

Table I. Generic Properties of Weapons

Advantages	Problems
"Zero" time of flight	
Rapid rate of fire	Weight and volume
Large available "magazine"	Radiation safety
Reduced requisite energy for kill	Operability
Limited collateral effects	Technological missing links
Nonnuclear	Complex, long-term R&D commitment
All-weather	Low-technology countermeasures
Complex, high technology	High risk
High payoff	

The genus is one of high risk and high payoff, and the deciding criterion for or against a CPB weapon may be
"Can this weapon perform a task that no other can?" A unique capability requirement could be stated in very practical terms:

- Does a CPB weapon provide a "real" ballistic missile defense?
- Can CPB weapons protect the surface fleet?

B. High Payoff Applications

The potential high payoff of CPB weapons can be illustrated by considering the example of a shipboard point defense weapon. The parameter space for assessment is a plot of engagement range vs. threat quality. By threat quality we mean the ensemble of characteristics such as velocity, maneuverability, radar cross-section, and arrival rate.

Figure 1 shows the space with the evolving threat to the surface fleet. Qualitatively we will describe the evolving threats as WWII aircraft, Early Missiles, Current Missiles and 1990's threat. The outer most range for guns is more than several km for large caliber artillery, but these ranges are only useful against low quality targets.

The early threats carried only high explosive (H.E.) warheads implying a keep out zone from the ship of the order of a kilometer. However, the modern anti-ship missile may carry nuclear explosives. The corresponding keep out volume would have a much larger radius even with additional hardening of the ship's superstructure. These keepout zones are shown as horizontal hashed lines in Figure 1.

The three panels of Figure 1 compare three defensive systems (dot-dash lines): guns, defensive missiles and CPB weapons. Gun projectiles are relatively slow and have long fly-out times to the threat. They can therefore be defeated by highly maneuverable offensive missiles. Even if gun systems are able to meet the current threat by extending the tail of the engagement curve, the offense can easily improve the threat quality, nullifying the defense.

Defensive missiles extend the engagement space out to the horizon, affording a potential for nuclear keep out. This potential is diminished because the kill probability of the defensive missile against the threat is low. To compensate defensive missiles are used in a salvo-look-salvo mode. The apparent defensive depth is needed to ensure eventual kills close-in. It is also extremely stressing to the sensor suite of the ship. The flyout plus target acquisition times set a minimum range for defensive missiles somewhat outside the non-nuclear keep out zone.

It is not our intention to discuss whether present defensive missiles actually meet the current threat. For our purposes it is sufficient to note that the offensive missible threat can easily out run defensive capability. The source of this asymmetry is twofold: 1) Because of finite response time, the defensive missile must be much more maneuverable than the threat if it is to counter evasive action by the threat. 2) Missiles are a mature technology at the top half of the S-shaped experience curve. Small improvements in the threat quality require much greater expenditures by the defense to close the marginal advantage. In other words technical advantage translates into advantage in system cost and development time as a technology reaches a mature state. It is highly unlikely that defensive missile will be able to counter the 1990's threat.

The solution to the defensive of surface ships against cruise missle attacks must be the development of a system which is insensitive to advances in threat quality. Particle beam weapons, if feasible, can be this solution. Because of the "zero-time-of-flight" characteristic, the beam is indifferent to threat speed; because the beam can deliver lethal energy to one target and be switched to another in milliseconds it is not sensitive to saturation attacks. Because they can catastrophically destroy a target just outside the keep out zone, a CPB weapon is less susceptible to defeat via radar cross-section reduction techniques. Envelopes for an early CPB (non-nuclear keep out) and advanced CPB are displayed in Figure 1c.

In this discussion the feasibility of controllable beam propagation and immediate catastrophic destruction of the threat have been assumed. These large assumptions are the focus of the DoD beam research program. The risk is high; the payoff, doing a unique defense task, is also high.

C. Configuration of Particle Beam Weapons Systems

We paint here a broad-brush picture of a CPB weapon and its major subsystems. A natural way to approach this problem is to trace the flow of energy through the system and onto the target. Realizing that this energy flow must be controlled in the context of a battle environment, we can draw a major-subsystem block diagram indicating subsystem relationships.

In Figure 2 we illustrate the flow of energy from its prime source to the target, noting that the system is designed in a basic scientific environment and operates in a certain battle environment. These last two items we will call exogenous systems. The interdependencies of the units of Figure 2 are managed by a command-and-control system, which includes the operator of the weapon. For the command-and-control system to function properly, it must have eyes and ears; this sensor suite may be included in the command-and-control subsystem or in the functional subsystems. We describe the subsystem components below.

1. Subsystem Descriptions

Prime Energy Subsystem

The prime energy subsystem must provide the source of energy that is to be converted into beam energy. The source energy will in general require conditioning so that it is in a form directly usable to the beam device.

Electrical power supplies may range from storage batteries and conventional power plants to magnetohydrodynamic generators or explosively driven generators. We expect that first generation devices can readily be powered by conventional generators. The energy so produced must then be stored and delivered as needed in the form of pulses of proper duration and shape. This latter task is accomplished by a network of switches and pulse-shapers connecting intermediate storage devices. The design of appropriate intermediate energy stores is likely to be one of the most challenging pulsed power tasks.

Beam Source Subsystems

The accelerator is the heart of the beam-source subsystem. The device is coupled to a beam-control subsystem (optics) that will allow the beam to be extracted from the device and sent to a beam director. One component of the subsystem will be an interface which permits the high power beam to pass from the vacuum of the accelerator into full density air.

The beam-control subsystem will contain magnetic beam-extraction and beam-transport devices appropriate to the beam energy. These components must be maintained in precise relative alignment so as to avoid degrading pointing accuracy.

The alignment is maintained by an active autoalignment system plus the platform on which the device is mounted. This platform is an important interface between the weapon system and its carrier.

Pointing and Tracking Subsystem

For its trip through the atmosphere (or space) the beam is directed and focused by an aiming system (nozzle). To enhance propagation this nozzle may contain pre-conditioning elements that tailor the beam rise time and quality.

The desired beam direction is determined by the command-and-control system from the information provided by two fine-tracking subsystems, one for the target and one for the beam. These trackers may be either passive (detect existing radiation produced by the beam and the target) or active (illuminate the tracked object). An attractive possibility is the use of the intense electro-magnetic pulse radiated by the beam as the target illuminator. Such a system would be inherently "self-bore sighted."

Beam Interactions

Once the beam has left the controlled environment of the weapon system, it faces a myriad of possible interactions with itself, with external electromagnetic fields, and with matter. Endoatmospheric beams of all particle types will suffer considerable energy losses due to atmospheric scattering; to reduce such effects charged-particle beams can propagate by creating a low-density channel through which the rest of the beam may propagate (hole boring). In such cases the energetics of hole-boring is a crucial issue in that it translates directly into beam device requirements. Charged particles will be affected by the geomagnetic field and by beam self-interactions. These self-interactions raise the question of beam stability and trajectory control.

The combination of beam propagation and target damage into the category of beam interactions emphasizes that the nemesis of propagation is the modus operandi of target damage. Such a realization may suggest novel beam possibilities.

Command and Control Subsystems

The flow of energy from the prime power source to the target is directed by the command-and-control subsystem. This system must coordinate the target search and acquisition radars and/or optical sensors with the pointing and tracking subsystem. If the target subtends an angle much greater than the aiming system accuracy an appropriate aimpoint must be selected on the basis of target imaging by the acquisition subsystem. The ambient environmental conditions must be appraised to determine relevant geomagnetic data. Not surprisingly, the operator will usually have to be assisted in the battle management by some form of computer and its associated decision algorithm software. Finally, full device management may require some means of assessing damage to the target.

Exogenous Subsystems

The CPB weapon system must function in an operational environment that is generally beyond its control. By this we mean that the system will have to meet certain size, volume, weight, and ambient-radiation requirements dictated by the system platform, be it a large capital ship or a hardened land-based bunker. The system cannot dictate the weather when the enemy chooses to begin the engagement. Furthermore, the system platform may significantly perturb the environment in a noncontrollable way.

If the system is to be more than a laboratory prototype, it must be operable safely by nonscientific personnel. Also, the system designer cannot ignore the economic or political climate, which may determine whether a particular weaponization concept will be approved.

III. AN OVERVIEW OF INTENSE BEAM PROPAGATION

A. Definition of Scope

In this section we present an overview of the propagation phenomenology of intense, relativistic charged, particle beams relevant to military applications. The key question is what kind of beam can propagate in a stable and efficient manner over a militarily useful distance from the beam source to the target. For most of the discussion we restrict our attention to electron beams. We conclude the description of propagation by discussing those features distinguishing electron from proton beams.

The electron beam may be considered to be a well-collimated collection of particles described by a particle energy E, a current I_b, a radius a, and a pulse length τ_p. Individual pulses are separated by a time τ_s. The beam particles are distributed with azimuthal symmetry about the axis of propagation, z. In a relativistic beam the particles travel with only a very small spread in their longitudinal velocity, $v_z; v_z = c$, the speed of light. We restrict our attention to beams in which perpendicular velocities, $v_\perp$, are small; that is $v_\perp / v_z < 10^{-1}$. Unless otherwise noted, we employ Gaussian units.

B. Basic Concepts of Atmospheric Propagation

1. Beam Dynamics

For a beam of charged particles to propagate unaided through the atmosphere, it must be self-focused; that is, it must be held together only by the magnetic field it generates. In a vacuum this is not possible because the force of electrostatic repulsion between particles exceeds their magnetic attraction.

2. Beam in Vacuum

Consider the simple example of a cylindrical beam with constant charge density, ρ, in the radial direction, r (Fig. 3). The current density, J_z, is $\rho v_z = I_b/\pi a^2$.

For radii, $r \leq a$, the magnetic field generated by the current is

$$B = \frac{2I}{a^2 c} r = \frac{2\pi\rho v_z r}{c} \qquad (1)$$

The charge density also generates a radial electric field outward;

$$E_r = \frac{2I r}{v_z a^2} = 2\pi\rho r \quad . \qquad (2)$$

These fields are large at the edge of the beam. For example, for $I = 10$ kA and $a = 1$ cm, $(E_r)_{edge} = 60\ I(A)/a(cm) = 600$ kV/cm; $(B_\theta)_{edge}(\text{gauss}) = I(A)/5\ a(cm) = 2$ kG.

These fields exert nearly equal and opposite forces on the particles; that is,

$$\begin{aligned} F_r &= q\, E_r - \frac{v_z}{c} B_\theta \\ &= 2\pi\, q\, \rho\, r \left(1 - \frac{v_z^2}{c^2}\right) \end{aligned} \qquad (3)$$

The forces cancel to within a factor $1/\gamma^2$, where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the measure of particle energy in units of the particle rest mass. Nonetheless, the net force is always defocusing--radially outward. In practice, the space charge defocusing of high energy electron beams in vacuum can be ignored when compared to the expansion of the beam due to the finite average value of $< v_{\perp}^2 >$; i.e., the beam expands due to a finite "thermal pressure."

3. Beam in Gas

A beam passing through gas ionizes molecules and thus builds up an electrically conducting channel. The conductivity σ so produced is generally sufficient to "short out" the beam's electrostatic field leaving only the focusing magnetic field. As described below, an equilibrium is set up in which the outward directed "thermal pressure" of the beam particles is balanced by the inward directed force of the magnetic field.

The high conductivity regime is established very shortly after the beam head enters a region of cold gas. At gas pressures such that the mean free path of secondary electrons is much less than the beam radius, a, the secondary electrons will diffuse out of the beam region on a time scale described by the conductivity, σ. Through this process, the beam's initial radial field, E_r, will be shorted out on a time scale $(4\pi\sigma)^{-1}$ -- ϵ_0/σ in MKS units. Near the beam head σ is changing rapidly as the beam ionizes the gas. Hence the formation time τ_f of the high conductivity regime is described by the amount of beam required to produce this condition.

At pressures greater than 100 Torr, we can neglect avalanche ionization due to E_r. Then the dominant process is direct collisional ionization of the gas. For I in kiloamperes the formation time is given by

$$\tau_f{}^2 \sim \left(\frac{1}{I(kA)}\right) \frac{a^2}{c^2} \quad . \tag{4}$$

Thus, we see that with just direct ionization, the beam will short out its radial electric field within a distance of the order of a beam radius behind the beam head. In realistic beams variation in beam radius near the beam head modifies this simple description.

For the body of the beam to maintain a finite radius in the presence of the pinch magnetic field, there must be an outward "thermal" pressure to balance the inward field pressure. The thermal pressure will be related to the value of $v_\perp^2$ averaged over the beam particles.

The ensemble of beam particles may be described by a plot of transverse phase space (Figure 4) at any instant of time. Each particle is represented by a single point in phase space. As the beam propagates each point, describes an orbit in phase space; thus the phase space volume occupied by the beam can evolve in time. By Liouville's theorem this volume and the density of points within it remain unvariant in the absence of dissipative processes such as scattering. Accelerator physicists define a quantity called normalized emittance which is of use in beam optics calculations.

$$\varepsilon_y = \beta\gamma A(y,\ v_y/c) \qquad (5)$$

where $A(y,\ v_y/c)$ is the area of the beam phase space.

A related macroscopic definition of the emittance (or without the factor of π -beam quality, Q) is of practical use since it can be measured. One definition is

$$Q^2 = \frac{v_{\perp max}^2}{c^2} \; R_{max}^2 \qquad (6)$$

An alternate definition uses the rms values of $v_\perp^2$ and r^2. The importance of the macroscopic emittance is that it characterizes the kind of beam which an accelerator system can transport successfully. It also sets the equilibrium radius of a beam in gas. In terms of the Alfven current,

$$I_A = \frac{m_e c^3}{q} \beta\gamma = 17000\ \beta\gamma(\text{amps}) \tag{7}$$

the equilibrium radius is related to the beam quality by

$$a_{eq} = Q\left(\frac{I_A}{2I}\right)^{1/2} \tag{8}$$

The initial value of Q in the accelerator is determined by the nature of the electron source. Factors leading to low values of Q include:

- drawing the electrons from a reservoir at low electron temperature
- avoiding beam scattering
- avoiding rapid variation in beam radius
- keeping B_z near zero at the cathode

Standard adiabatic theory shows that γQ is an invariant if the beam is accelerated gently. In the absence of any beam-accelerator coupled instabilities, the equilibrium radius of the beam in gas will scale as $\gamma^{-1/2}$. Small radius is achieved by producing good quality beams at high energy. For example, the Astron accelerator at Lawrence Livermore National Laboratory produced a high quality ($Q = 10^{-2}$ rad-cm) beam of 5 MeV electrons with a current of 0.5 kA. The equilibrium radius of this beam in gas was approximately 0.15 cm as predicted by Equation (8).

4. Beam Expansion and Energy Losses

Unfortunately, the very interaction of the beam with gas which allows self-focusing also degrades the beam intensity. Degradation takes the form of decreased beam energy and expansion of the beam radius.

As the beam particles pass through the gas, they suffer many small angle deflections from encounters with nuclei and electrons. Each of these scattering events contributes to increasing the transverse velocity spread of the beam. The consequent increase in beam emittance implies an expansion of the equilibrium radius of the beam in accordance with Equation (8).

A quantitative evaluation of this effect leads to the Nordsieck equation

$$\frac{1}{a}\frac{d\,a}{d\,z} = \frac{7.4 \times 10^{12}\ (\text{watts})}{\lambda_R P} \tag{9}$$

where P is the instantaneous beam power and λ_R is the interaction scale length. For an electron beam λ_R is the radiation length (= 300 ρ/ρ_0 meters); ρ is the gas density and ρ_0 is the normal air density. The e-folding distance is called the Nordsieck length, L_n.

The Nordsieck expansion has been measured in experiments with the Astron beam in the presence of an external guide field. In these experiments the beam emittance had been spoiled so as to result in a beam radius of 1 to 1.5 cm before injection into a tank filled with dry nitrogen. The beam radius was measured at several z positions for several gas densities as shown in Figure 5. The dashed curve represents the predictions of the Nordsieck Equation (9). The agreement between the calculation and measured radii is generally good especially for the small gas number densities. As the gas density, and therefore the scattering frequency, becomes higher, the quasi-static change in emittance assumed in the derivation of Eq. (9) is less valid. A more complete derivation including dynamical effects in a beam envelope equation yields the better predictions shown as solid lines in Figure 5. The envelope equation relates a scale radial dimension of the propagation beam to macroscopic internal forces, external fields and interactions with a background gas via scattering. Careful derivation of a general envelope equation for cylindrically symmetric beams has been given by Lee and Cooper.*

There are three significant mechanisms for energy loss from the beam particles: direct loss to the gas electrons, emission of gamma rays in collisions with nuclei, and ohmic loss.

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*E. P. Lee and R. K. Cooper General Envelope Equation for Cylindrically Symmetric Charged Particle Beams, Particle Accelerators, 7, Pp. 83-95 (1976).

C. Direct Loss

The direct loss is the energy expended in exciting, dissociating, and ionizing the molecules, and scattering free electrons. In a good approximation, the energy lost is simply proportional to the total number of gas electrons in the path of the beam particle.

The direct loss is essentially independent of beam energy. We write

$$\left(\frac{\partial}{\partial z} mc^2\right)_{\text{direct}} \simeq - a\rho, \tag{10}$$

with ρ the gas mass density and $a \simeq (1.5\text{-}4)$ MeV depending on the gas and γ. For air $a \simeq 3$ MeV cm^2/g. An electron-ion pair is created for every 34 eV lost from the primary particle; this is the principal mechanism for building up σ in dense gas at the head of the beam.

D. Radiation Loss

When a particle is scattered by a nucleus, a gamma ray may be created by the acceleration. The energy E of this photon ranges from zero up to γmc^2, but with probability decreasing as E^{-1}. The beam energy lost per encounter is thus of the form

$$\overline{\Delta\gamma mc^2} = - \frac{\Delta z}{\lambda R} \int_0^{\gamma mc^2} \frac{dE}{E} \cdot E = - \frac{\Delta z}{\lambda_R} \gamma mc^2 , \tag{11}$$

Here, λ_R is the radiation length in gas of density ρ; for air $\lambda_R = 300$ m. The value of λ_R^{-1} scales as $nZ(Z + 1)$ in which n is background number density and Z is the nuclear charge. From Eq. (11) we write

$$\frac{\partial}{\partial z}\left(\overline{\gamma mc^2}\right)_{\text{radiation}} = - \frac{1}{\lambda_R} \overline{\gamma mc^2} , \tag{12}$$

so the mean energy tends to decrease exponentially with distance. Radiation loss dominates over direct loss if $\gamma mc^2 \geq 120$ MeV in air.

An important aspect of radiation loss is its statistical character. Since the probability of creating a photon decreases only as E^{-1}, energy loss is dominated by a few medium to high energy photons rather than the many created at low energy. This means that γ itself is uncertain for a particle after it has traveled a fraction of λ_R - only the mean γ of a collection of beam particles is known with certainty. On the other hand, direct loss is the result of many small energy decrements, so it does not cause significant uncertainty in γ.

E. Ohmic Loss

The Ohmic loss (drag) is a collective effect associated with the modulation and chopping of the beam current. A changing current induces an axial electric field in channel,

$$E_z = -\frac{L}{c^2}\left(\frac{\partial I}{\partial x}\right)_z \tag{13}$$

where x is a retarded time variable, $x = ct - z$. The quantity L/c^2 is an inductance per unit length characterizing the channel ($L \approx 4.5$). The axial electric field drives a plasma current, I_p, given by $I_p = \pi a^2 \sigma E_z$. Hence the current appearing in (13) must be the net current $I = I_p + I_b$. The field E_z causes the beam particles to lose energy

$$\frac{\partial}{\partial z}\left(\gamma m_e c^2\right)_{ohmic} = - e E_z \tag{14}$$

The effect on the pulse as a whole is described in terms of the beam current averaged value of the retarding field, $< E_z >$. To first approximation the ohmic loss is independent of the gas density.

A related concept is the ohmic range which is the maximum distance a pulse can propagate before all its energy is lost in ohmic heating of the plasma channel. If the initial particle energy is mc^2, then

$$Z_{ohmic} = \left(\gamma mc^2\right) / \quad -e < E_z > \quad . \tag{15}$$

Actually γ also decreases due to ionization and bremsstrahlung losses and $< E_z >$ depends on the local channel density, so Eq. (14) strictly applies locally at a position z:

$$Z_{ohmic}(z) = \frac{\gamma(z)mc^2}{-e < E_z >_z} \tag{16}$$

This definition applies to all modes of propagation. The values of $< E_z >$ range from 100-300 MeV/km depending on pulse train structure.

F. Holeboring

Both the energy loss and Nordsieck expansion of the beam prevent any single pulse from propagating much more than a radiation length. If the range of the pulse is to be pushed out to an ohmic range, the direct and especially the Bremsstrahlung losses must be reduced. If the beam is to maintain a high power density out to long distances, the Nordsieck length must be increased. In other words, the radiation length must be increased to the order of the ohmic range.

Because the radiation length λ_R is proportional to gas density, kilometer ranges can be produced by reducing the density in the beam channel. This effect (called holeboring) occurs automatically with a sufficiently intense beam because it heats the channel causing it to expand. The first pulse in a pulse train (or bolt) expends its energy in its way and eventually is lost, but it opens the low density hole through which the rest may pass. This process is repeated over and over as successive pulses become the lead pulse and lengthen the hole out to multi-kilometer ranges.

The limiting range for self-focused beam propagation will depend upon the details of the pulse train wave form (propagation mode) and the temperature of the low density channel. Because of the direct dependence of bremsstrahlung and ionization losses on channel density, the energy transmission efficiency for a beam in a well formed channel will depend upon the channel temperature. The peak temperature in the channel is determined by a balance between energy deposition by the beam and energy loss from the channel.

The speed and efficiency of the holeboring process is strongly dependent upon hydrodynamic processes. These processes have a characteristic time of the order of the beam radius divided by the sound speed in the air. Clearly the energetics of holeboring are also improved by minimizing the volume of air which is to be heated to high temperature. If the energetics of creating low density channels are not to exceed $\sim$ 1 MJ/km, initial beam radii $\sim$ 1.0 cm are required. The minimum desirable beam radius depends upon stability considerations peculiar to the choice of pulse waveform. For centimeter radius beams holeboring rates will be of the order of a kilometer per millisecond.

G. Requirements for Beam Stability

The simple model of a long, continuous beam pulse burning through the air is complicated by the existence of several instabilities that can disrupt the beam. The most important of these instabilities is the resistive hose mode which is a sideways displacement of the beam from the conducting channel. A large body of theoretical and experimental results suggest that pulse parameters may exist with acceptably small hose-mode growth for beams in full density air. The present DARPA beam technology program is aimed at exploring this issue.

1. <u>The hose instability of a continuous beam</u> - The conductivity generated by the passage of the beam through gas is much larger than that required to short out the repulsive electric field. This fact has the undesirable consequence of the resistive hose instability. The beam as a whole may undergo transverse ejection from the channel or disruption. If σ were very low (say σ a/c < 1), then the magnetic field would always be centered around the beam axis, and there could be no net sideways force. On the other hand, with infinite σ the magnetic field is "frozen in," and the beam, if perturbed, undergoes simple harmonic motion around the field axis at the betatron frequency. In reality σ is finite, so displacement of the beam is able to feed back on itself via the disturbed field, which responds on the magnetic diffusion time

(or skin time) $\tau_m \approx 4\pi\sigma a^2/c^2$. For centimeter beams with currents of tens of kiloamps τ_m is 5 - 10 ns. The hose disturbance will grow as the beam propagates e-folding in about half a betatron wave length,

$$\lambda_\beta = 2\pi a \left(\frac{I_A}{I_B}\right)^{1/2} .$$

For a 50 MeV, 10 kA electron beam with a 1 cm radius, the e-folding distance is only $\sim$ 0.5 meters.

2. Pulse modes - The choices of pulse length and interpulse spacing in a pulse train distinguish pulse propagation modes; these may be considered ways of minimizing beam disruption and extending the range of controllable propagation. The considerations which underlie the choice of pulse train structure derive from the nature of the potential beam instabilities. Since a transverse perturbation convects backwards in the beam frame as it grows, a short enough pulse will be effectively stable. This suggests that the bolt can be stabilized as a whole if it is chopped into many short pulses. The length of each pulse must not be very much greater than a skin time, since this is roughly the growth length of the instability, and the separation of the pulses must be large enough that the disturbance decays away between them. On the other hand, the pulses cannnot be separated so much that they are decoupled, unless also vanishes between pulses. In that case the fields which couple successive pulses will vanish. Consequently on by the interaction of the beam with the remaining low density channel must provide pulse-to-pulse coupling.

As a pulse enters the low density channel density gradients give rise to conductivity gradients which allow an electrostatic guiding of the leading edge of the pulse. The nose of the pulse in turn provides the B-field and high conductivity to guide the body of the pulse through the low density channel. A simplified model experiment of this channel tracking mechanism has been provided by the stable propagation of low energy (1.5 MeV), high current (15 kA) beams in low density gas in Lucite tubes of several centimeters radius. Beams have also been observed to follow bends in such tubes.

3. Choices of Beam Parameters

Current

The growth rate of the hose mode is limited by the generation of electrical conductivity in the channel. A simple analytic model predicts a maximum head-to-tail amplification factor during the period of growing conductivity:

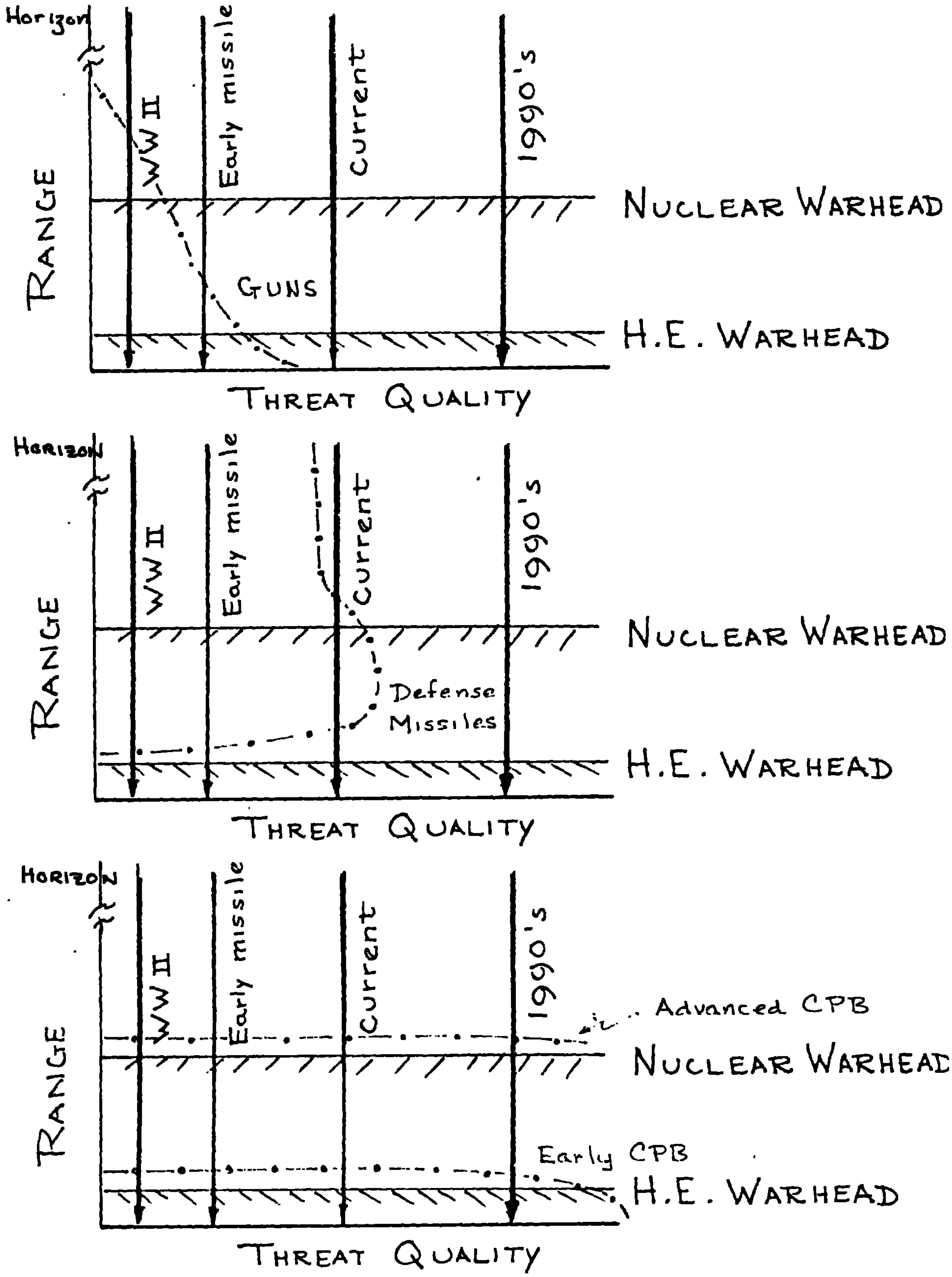
$$A \simeq e^{0.69/(d\tau_d/dt)}$$

where

$$\tau_d = \frac{1}{8}\,\tau_m = \frac{\pi\sigma a^2}{2c} \quad .$$

For reasonable limits on growth $d\tau_d/dt > 0.2$; in other words the conductivity in the channel must grow rapidly. Assuming generation via direct ionization only, sufficient conductivity growth can occur if the beam current exceeds several kA. Any feasibility demonstration must satisfy this condition regardless of other details of the pulse train structure. Similar considerations lead to the requirement that the rise time of the current pulse τ_r, be less than 1 ns.

A requirement of high particle energy for weapon grade beams derives from several considerations. Not the least of these is lethality of the pulse; i.e., beams should deliver megajoules of energy to the target in short times. With respect to propagation physics, the Nordsieck equation(9) requires that the beam power must exceed 7×10^{13} watts to prevent catastrophic beam expansion over less than a radiation length. Studies by the inertial fusion community indicate that the cost of linear induction accelerators scale as the square root of beam energy. Therefore, one would like to choose relatively low energy in a feasibility demonstration device. For low energy beams, however, beam expansion due to scattering can obscure the magnitude of the hose disturbance. Therefore meaningful studies relevant to the stability of beams in full density air require beams with modest particle energy. The energy must be sufficiently high that the Nordsieck length be several betatron wavelengths. Such considerations set a lower limit somewhat below 50 MeV for a demonstration of stable propagation of intense electron beams through the atmosphere.


Horizon
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THREAT QUALITY

Figure 1

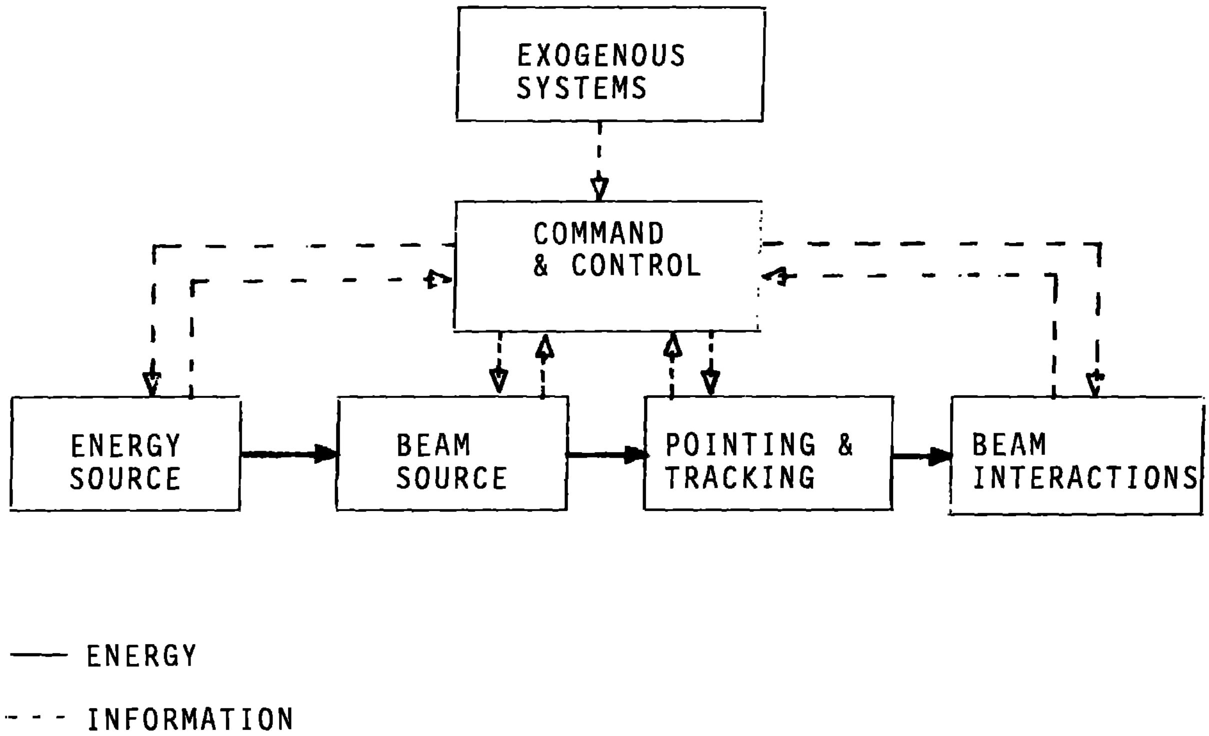


Figure 2 - Major Subsystems of CPB Weapons

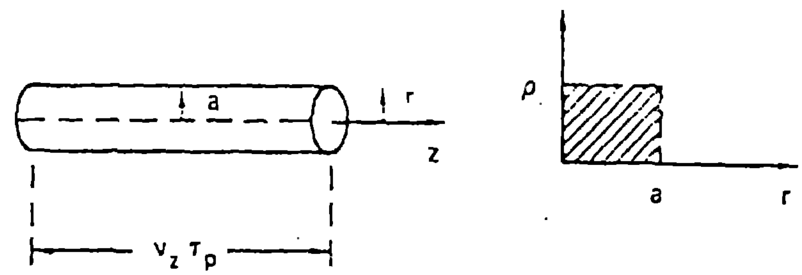


Figure 3 - Geometry and Radial Profile of a Cylindrical Beam

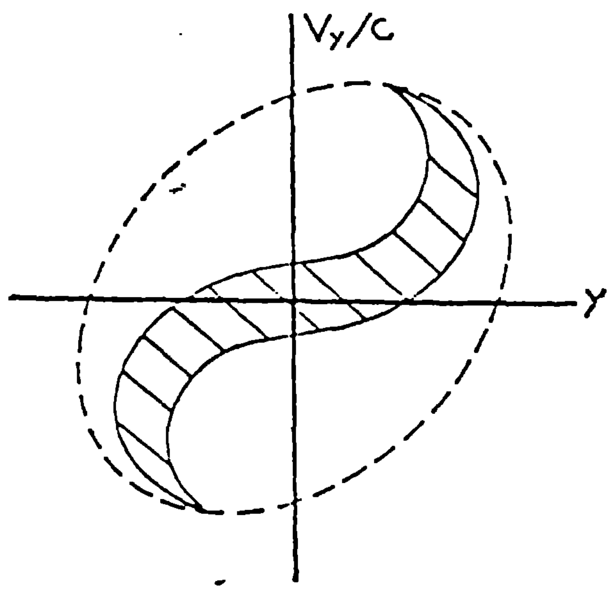
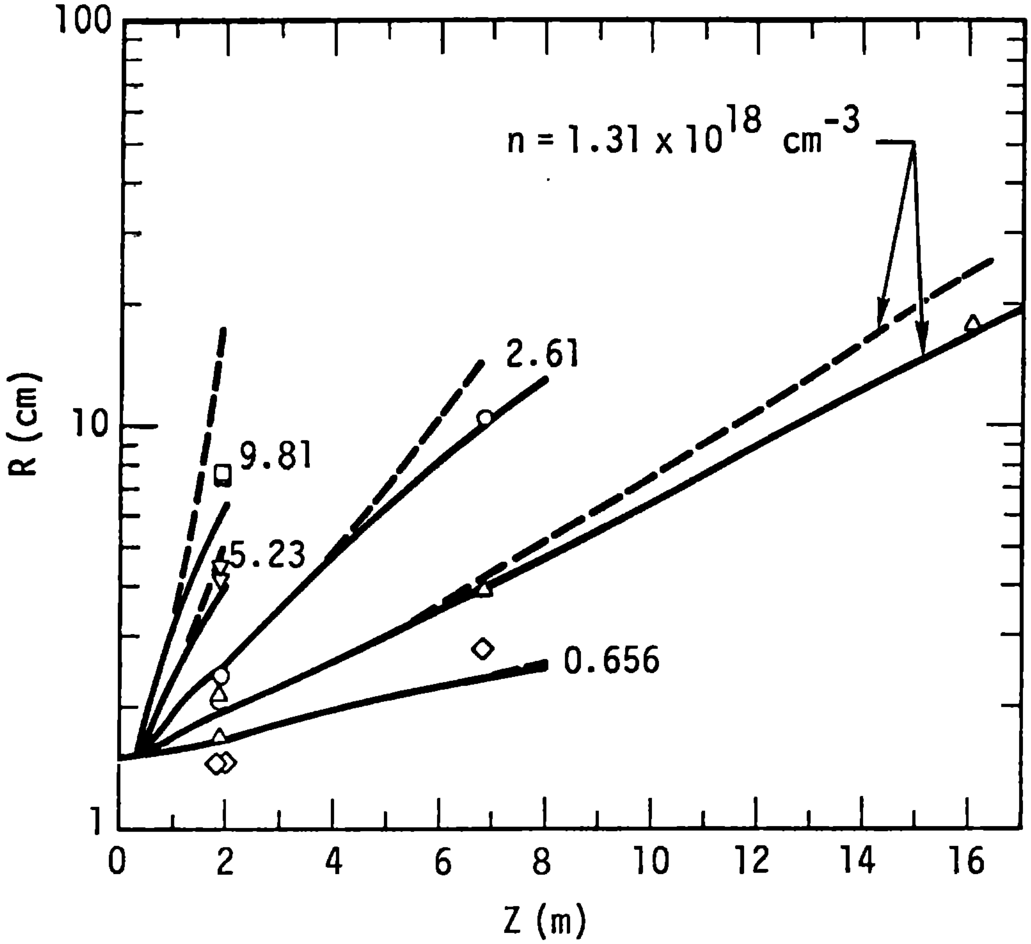


Figure 4 - The shaded region represents the actual area occupied by the beam with a distorted emittance; the dashed ellipse outlines the effective emittance.



N_2, 210A, γ = 11

Figure 5 - Nordsieck Experimental Data

APPENDIX A

Generating Intense Electron Beams for Military Applications

Although charged-particle beams represent a potential breakthrough in military capability, their future use as weapons depends on the feasibility of propagating an intense, electromagnetically self-focused electron beam through the atmosphere. LLNL researchers hope to determine this by conducting a comprehensive program of electron-beam propagation experiments in a 50-MeV Advanced Test Accelerator Facility (the ATA)[1] that we are constructing at our high-explosives test location, Site 300. This facility, the successor to LLNL's Astron II and Experimental Test Accelerator (ETA), will cost about $50 million and should be completed by the fall of 1982.

The ATA, together with its associated program of beam-propagation physics, represents the largest single component of the Particle-Beam Technology Program conducted by the Defense Advanced Research Projects Agency (DARPA). This program was formerly sponsored by the U. S. Navy, and the Naval Surface Weapons Center is now the direct funding agency for the DARPA program. The aim of this program of research and exploratory development is to resolve those scientific issues necessary to show that particle-beam weapons are possible. The prime goal of the DARPA Particle-Beam Technology Program is to resolve what is and is not possible in beam propagation. Accordingly, our goal with the ATA is to develop an experimental capability that can answer critical questions about beam-propagation physics in a timely and cost-effective fashion.

Although we can study many aspects of beam stability and propagation in a shielded experimental gas-filled tank, it is essential to test particle beams in open air to determine how the beam will propagate in various natural environments. In addition, we must be able to fire the beam in a range of directions to test methods of pointing and tracking. Finally, an outdoor facility will allow us to detonate safely substantial quantities of chemical explosives in target-damage studies.

Potential hazards associated with the ATA experiments were considered in choosing our site. LLNL's Site 300 is located in a remote area 25 km southeast of LLNL that is well-equipped for managing such experiments. The ATA is being built in a shallow valley to exploit natural shielding. Figure 1 shows the ATA facility under construction.

APPLICATIONS OF INTENSE BEAMS

Recent advances in pulsed-power technology, notably the development of repetition-rated electrical components (i.e., ones capable of delivering short pulses of high-voltage, high-current electrical power many times per second), have made feasible a number of high-technology uses for intense electron beams. Figure 1 illustrates several applications for electron beams, defined by their beam parameters. The illustration does not distinguish regions of early research from regimes of final application, nor does it exhaust the possible applications. Of the wide variety of possible applications, flash radiography and nuclear effects simulation have considerable military significance. In their application in the free-electron laser, such beams have attracted considerable interest in the scientific and defense communities. The military application that has received the most public attention is the use of intense beams of charged particles as point-defense weapons.

If it proves feasible to propagate charged-particle beams, their first use as weapons will be largely against targets within a few kilometres or less. Since they are so lethal, charged-particle beams can be used at distances too close to allow time for the "second shot" that might be necessary with less effective weapons. Early uses of the beams might be to defend large ships from cruise missiles[2] or for the close-range defense of hardened sites such as missile silos or national command authority centers. Such missions are called "point-defense" missions in distinction to area-defense missions.

Although the beam must bore its way through the air to the target, this process takes at most a few thousandths of a second. The deposition of megajoules of energy in the target is almost instantaneous. Therefore, beam weapons have the potential for engaging tens of targets per second, depending upon certain constraints in the system that controls their firing. These characteristics make beam weapons particularly well suited for countering small, very fast, highly maneuverable threats.

Accelerators have the demonstrated capability to convert upward of 30% of their prime electrical power into beam energy. If the electricity is produced with conventional generators powered with jet fuel, megajoules of beam energy can be produced with the consumption of approximately 10 litres of fuel. Consequently, even modest fuel supplies translate into a very large reserve of "ammunition" for a particle-beam weapon. This reserve makes it extremely difficult to overwhelm the particle beam with a large number of incoming threats.

Upon striking a target, the beam penetrates deeply and deposits its energy in a long, narrow cone. The high-energy electrons in the beam can penetrate tens of centimetres of solid aluminum, making it very difficult to shield against them. Damage to the target is immediate and severe; it includes structural damage, destruction or disruption of electronics equipment (e.g., missile guidance systems), and nearly instantaneous detonation of chemical explosives. An example of the damage a charged-particle beam of small radius can inflict on a target is shown in Fig. 2.

Not all the energy in a pulse reaches the target; some of it is lost in the atmosphere at a rate roughly proportional to the density of the air. Under normal conditions, the pulse will lose half its energy after traveling about 200 m. However, this loss rate does not limit the beam's range as much as might be expected. Much of the energy lost from the pulse goes into heating the air along the path of the beam. In a few microseconds, this hot air expands, leaving a channel of much lower density that the next pulse can follow with minimal energy loss. The use of bolts consisting of strings of pulses may allow propagation over long distances.

The electrons in the pulses scatter as they pass through the air, and the beam gradually widens. Because this spreading reduces the beam's power density on the target, the beam is useless as a weapon unless the spreading is inhibited. The large currents in the beam wrap it in a strong magnetic field (proportional to the current) that limits spreading by pinching the electrons closer together. This self-focusing occurs only when a high-current beam is traveling through the air or some other gas. Self-focusing keeps the beam diameter down to a centrimetre or so in air. When the focused beam hits the target, it deposits large quantities of energy in a small volume. The high-energy density makes the beam lethal.

	Astron II[a]	ERA[b]	ETA[c]	ATA[d]
Beam energy, MeV	6	4	4.5	50
Current, kA	0.8	1.2	10	10
Pulse length, ns	300	30	40	70
Burst rate, Hz	800	2	1000	1000
Average rate, Hz	5	2	5	5

[a] Lawrence Livermore National Laboratory, about 1968-1976.
[b] Electron Ring Accelerator (Lawrence Berkeley Laboratory).
[c] Experimental Test Accelerator (Lawrence Livermore National Laboratory).
[d] Advanced Test Accelerator (Lawrence Livermore National Laboratory).

THE ATA'S ROLE IN PARTICLE-BEAM RESEARCH

The particle energy in a beam weapon determines how deeply the beam will penetrate the target. Although the ATA's energy level of 50 MeV will not cause beam penetrations as deep as more energetic beam weapons would, the ATA should provide data applicable to the designing of beam weapons. The ATA should enable us also to measure the radiation cone that extends far from the beam itself. (This radiation cone can cause significant damage to electronics equipment, thus increasing the effective range of a particle-beam weapon.) In both cases, scaling laws must be applied if we extrapolate our data to particle-beam weapons. Regardless of how our findings finally are applied, many complex weaponization issues will arise in the transition from the ATA to beam weapons.

Even though the particle energies of the ATA facility are well below those projected for beam weapons, we should be able, with high confidence, to extrapolate positive test results to increased energies. This close programmatic link between theory and experiment makes the ATA a cost-effective means for studying the physics of particle-beam weapons.

The ATA represents several large advances in high-intensity accelerator technology. The beam characteristics projected for the ATA (10-kA current, 50-MeV particle energy, 70-ns FWHM pulse, and 1-kHz repetition rate) are far beyond the capabilities of any existing accelerator. Table 1 compares the parameters of the ATA with those of the Astron II, the ETA, and the Lawrence Berkeley Laboratory's electron ring accelerator (ERA) injector.

In our experiments, we would like to test charged-particle beams over as wide a range of physical parameters as possible. The advantages to be gained from such exhaustive testing must, of course, be weighed against both the costs and the physical limits of the accelerator.

The ATA will enable us to determine the conditions under which stable and controllable beams can be propagated in open air. We can also test the beam's capability for inflicting dasmage and the performance of the nozzles that steer or aim it. As part of our effort to design a system for pointing and tracking, we will measure the degree to which microwaves or optical means can detect the beam path.

The particle energy of the ATA will be ten times that produced by the ETA. This increased particle energy means the ATA will have an order of magnitude more accelerator modules than the ETA, placing great demands on hardware reliability. The large number of components also makes it necessary to keep accelerator instabilities in mind when designing the beam-transport unit, because the focusing requirements are unusually stringent.

To ensure this high level of component reliability, we are using the ETA to test ATA technology on a small scale. The ETA will be used to verify the projected performance levels of the electron source, the 1-kHz pulsed-power components, and the beam-control system for the ATA. Since its initial operation in mid-1979, the ETA has achieved all design goals and has produced several million beam pulses. The ETA, therefore, has provided the necessary data base for design of high-voltage components for the ATA, which will produce a few million beam pulses per year in normal operation.

THE ATA DESIGN

The 200-m ATA Facility has an 85-m linear electron accelerator and consists of four major units: a pulse-forming network, an electron injector, a series of accelerator modules, and an experiment tank (see Fig. 3). The pulse-forming network provides short, high-voltage pulses that power the electron injector and accelerator modules. The injector produces a 10-kA beam of 2.5-MeV electrons, which are guided by magnetic fields through an accelerator consisting of 190 separate accelerator modules (cavities). The accelerator increases the electron energy to 50 MeV in 190 separate increments of 0.25 MeV. When they are at full energy, the electrons, still guided by magnetic fields, pass into an experiment tank that contains gas of variable type and pressure and that is covered with a thick layer of earth and concrete to absorb any stray radiation.

PULSED-POWER NETWORK

The pulsed electrical power is provided by a pulse-forming network (Fig. 4) that stores a discrete amount of energy over a period of time in order to compress it and then suddenly releases it as a pulse. The power is stored in components such as an electrical transmission line that is charged to a desired voltage in much the same manner as a capacitor. A transmission line (Blumlein) composed of three concentric, metal conducting cylinders is frequently used in pulsed-electron accelerators.

Figure 4 shows how energy is converted to the beam from primary ac power. The ac power drives a high-voltage dc power supply which, in turn, feeds an energy storage and charging network. The pulse from this network is stepped up to 250 kV by a resonant transformer bolted to the Blumlein transmission line. When the current that has charged the Blumlein drops to zero, a spark-gap switch (filled with gas at high pressure) is fired by a 150-kV trigger circuit. The resulting high-voltage discharge from the Blumlein is then impressed across the accelerating gap.

As long as this pulse persists, electrons passing by the gap will be accelerated. The energy stored in the Blumlein in 10 μs is delivered to the acceleration cavity in 70 ns, almost 150 times faster.

The Blumlein can be recharged (by having an insulating gas flow through the spark-gap switch at high velocity) and then fired again at a 1-kHz burst rate. The voltage-holding ability of this switch (developed for ATA) determines the maximum accelerating voltage per ATA module. Because of limitations in the energy-storage subsystem, the spark gap is fired in bursts of ten consecutive pulses with two-second rests between bursts.

ELECTRON INJECTOR

The source of the high-current electron beam is the electron injector, or gun. The ATA's 2.5-MeV electron injector, the second major unit in the accelerator, is typical of the pulsed-power technology used throughout the system. Acceleration voltages in both the electron injector and the accelerator module are generated by similar power-supply and pulse-forming networks feeding the ferrite induction cores.

The 10-kA current produced by the injector requires special design features to control the defocusing effects of the electromagnetic fields the beam itself generates. These fields lead to a net force that is the difference between the electrostatic self-repulsion of the electron cluster and the magnetic pinch forces that tend to hold the beam together. For beams with kinetic energy greater than their rest mass energy, these forces nearly cancel (the net repulsive force is proportional to the inverse square of the beam energy).

Figure 5 is a schematic cross section of the ATA's electron injector. Here (as in a conventional vacuum tube) a high-voltage pulse is applied to a grid to extract the required current from the cathode.

In the vicinity of the grid, the repulsive self-fields of the beam are shorted by the grid; this causes an initial focusing of the beam (as Fig. 5 shows). When the grid pulses, the anode is pulsed simultaneously to 2.5 MV, rapidly raising the kinetic energy of the electrons as they traverse the region between the grid and anode. Although the defocusing forces are reduced by the increase in beam energy, solenoidal coils are needed to control and focus the beam for transport through the accelerator module.

The electron injector is constructed in two parts, each with five 0.25-MV induction units in series to provide the 2.5-MV anode/cathode voltage pulse. This voltage also appears across two large ceramic accelerator columns thast are divided by metallic rings into ten segments. The segments are connected by power resistors to ensure proper voltage distribution across the column to avoid electrical breakdown. The accelerastor columns also serve as the barrier between the vacuum in the beam area and the dielectric oil that fills the induction units. The division of the injector into two parts has several advantages: it provides a vacuum pumping port in the center of the injector, partially shields its ceramic insulators from the electron beam, and makes assembly easier.

THE ACCELERATOR MODULE

The accelerator module is the heart of a multistage accelerator like the ATA. Each accelerator module adds an incremental kinetic energy to the beam. Therefore, by increasing the number of modules that make up the accelerator, one can increase the beam energy to any desired level. In a qualitative sense, the linear induction accelerator is just a series of one-to-one pulse transformers. The primary circuit of the transformer is the pulse-forming network previously described. The secondary circuit of the transformer is the electron beam itself. As Fig. 6a illustrates, the primary circuit loops around the magnetic core once, just as the electron beam threads through each core once. In such a transformer, the voltage induced in the secondary circuit is just that in the primary circuit.

The acceleration process can be described more specifically (Fig. 6b). Before the beam enters each cavity, the ferromagnetic cores are magnetized (set) to a maximum magnetic field. Then, a voltage pulse from the coaxial transmission line is impressed upon the acceleration gap. The ferrite torus acts as an inductance, initially preventing a large current from flowing through the structure around the ferrite, thereby keeping the coaxial line from shorting. In accord with the law of magnetic induction, this current increases at a steady rate given by the ratio of the voltage pulse to the ferrite inductance. In addition, the magnetic field in the core decreases from its initial value at a constant rate until the field attains a minimum value. At this time, the applied voltage pulse ends. In addition to the time-varying fields that accelerate the electron cluster, there are static magnetic fields that guide the beam as it moves down the accelerator from one cavity to the next.

In induction accelerators, it is important that the voltage pulse to the acceleration cavity coincide with the arrival of one of the electron clusters that are passing through the accelerator module. Proper timing is ensured by appropriate delays in the triggering circuits of the pulsed-power network.

An important complication in any electron accelerator is that the traveling electron clusters generate electromagnetic fields that are modified by the accelerator structure. This coupling can distort the accelerating fields and limit the output current. It can also cause small, random perturbations in the beam's position or structure that lead to damaging or current-limiting instabilities. Because the beam fields increase with the beam current, these perturbations are especially serious in high-current accelerators. Furthermore, the current-limiting instabilities grow exponentially with the number of accelerator cavities. The unusually high beam current of the ATA and the ETA necessitates the choice of high voltage accelerator modules with toroidal ferrite cores rather than lower-voltage, soft iron units such as were used on the Astron. This choice reduces the number of accelerator structures that can interact with the electron beam, suppressing potential instabilities.

EXPERIMENTAL FACILITY

Once the electrons have acquired their final energy, 50 MeV, they are guided by a series of steering and focusing magnets into a large tank that can be filled with gas of various composition and pressure. This tank is located in an 80-m-long underground tunnel (Fig. 7).

The first experiments to be performed after the accelerator construction is completed will be measurements of beam current and voltage waveform and their variation on a pulse-to-pulse basis. We will measure also the spatial distribution and angular divergence of the beam. When we understand the nature of the beam and its pulse-to-pulse reproducibility, we will begin studies of beam stability and dynamics as well as beam interactions with gas and plasma.

For all such studies, we require accurate measurements. Line-of-sight holes from the ground surface into the tunnel provide a means of removing sensitive diagnostic equipment from the intense radiation environment the ATA beam will produce. A diagnostic bunker near the entrance to the tunnel will accommodate the fast diagnostics needed to study the physics of beam/gas interactions. Both the diagnostics for beam/gas interaction studies and the specially designed voltage and current probes will be monitored by the ATA control system to provide accurate and complete records of all experiments.

CONCLUSION

Our coordinated program of theory and experiments with the ATA has the goal of providing a complete understanding of beam-propagation physics. Our DARPA-funded program in particle-beam technology has yielded a body of knowledge about high-intensity accelerators and beam physics that we can build upon with the ATA. We expect to obtain high-quality, high-current electron beams with energies at least an order of magnitude greater than any other repetition-rated accelerator has produced. The ATA promises advances in high-intensity accelerator technology that are essential to a wide range of applications, including beam weapons.

NOTES AND REFERENCES

1. For information on the dedication of the Advanced Test Accelerator, see Energy and Technology Review (UCRL 52000-81-1), January 1981, p. ii.

2. W. E. Wright, "Charged Particle Beams. Could We? Should We?," Proceedings of the U.S. Naval Institute, U.S. Naval Institute Press, Annapolis, MD (November 1979).

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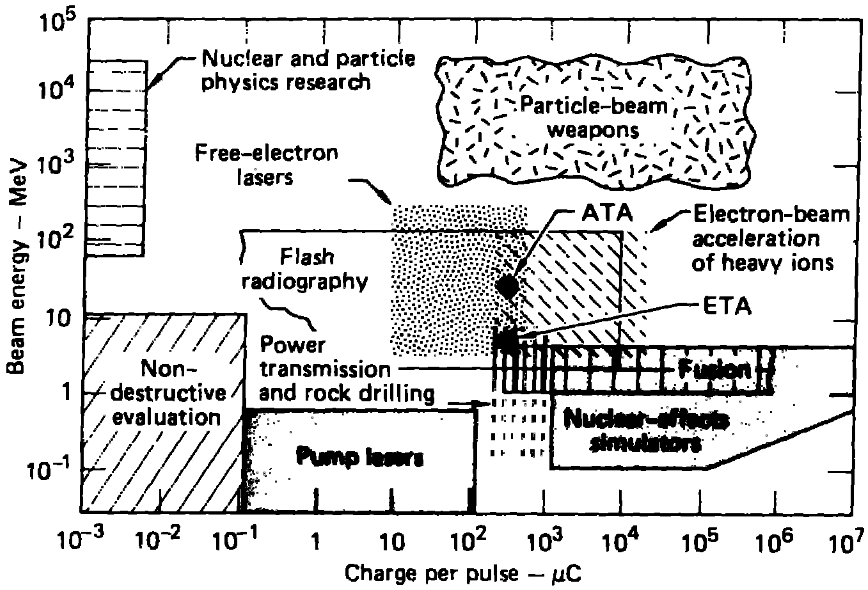


Figure 1 - Possible applications of charged-particle-beam accelerators. Applications of pulsed beams may be characterized, as indicated here, by the required beam energy and charge per pulse (the product of pulse length and current). The Experimental Test Accelerator (ETA), represented by the lower circle in the figure, and the Advanced Test Accelerator (ATA), represented by the upper circle, stand at the crossroads of scientific and technological applications of charged-particle beams.

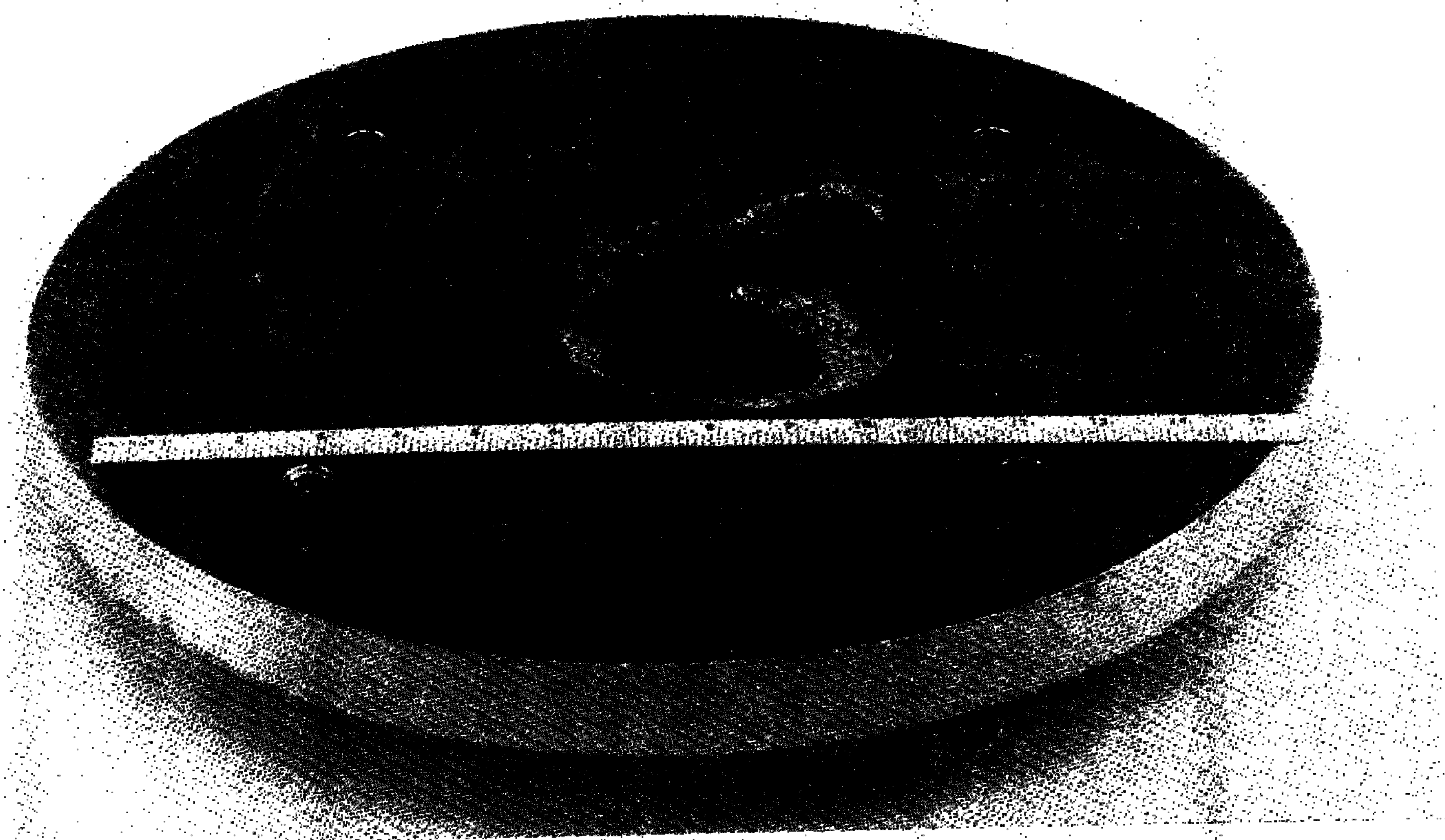
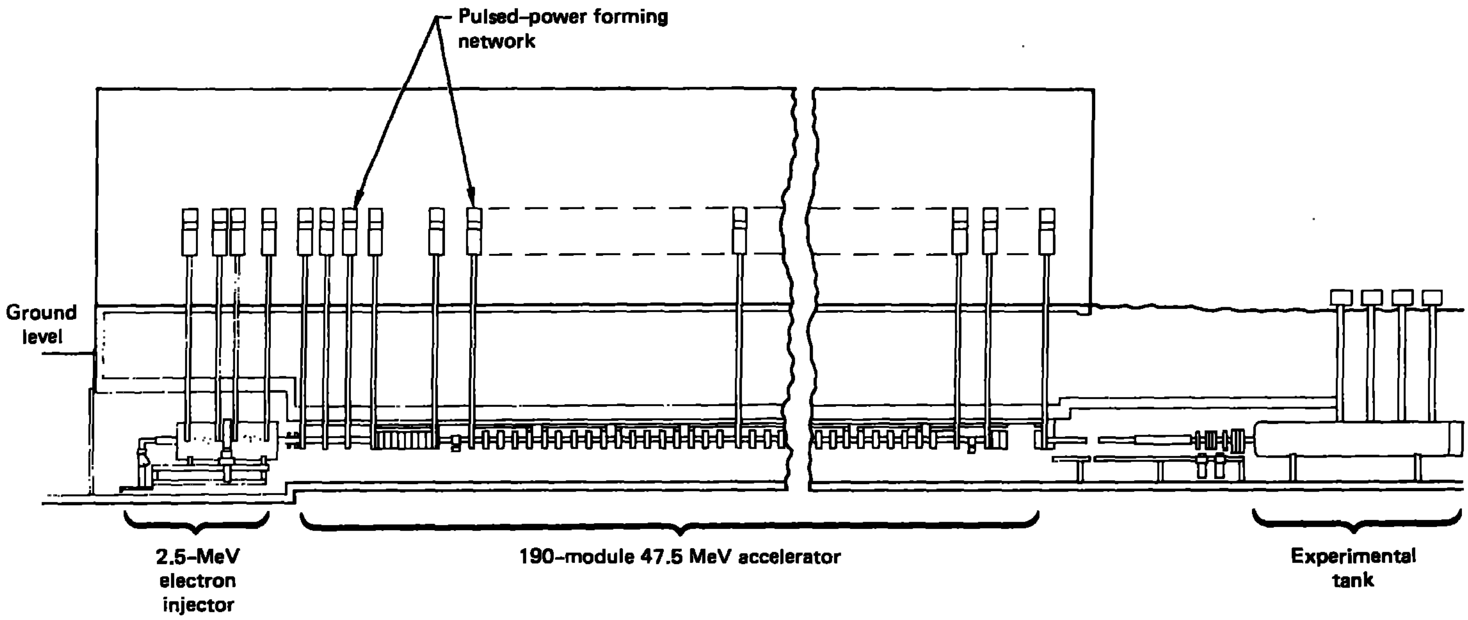


Figure 2 - An example of the damage charged-particle beams can inflict. This aluminum disk (1 cm thick and 16 cm in diameter) was hit by an electron beam with about the same energy content but one-fifth the particle energy of an ATA beam pulse. The beam penetrated about 0.6 cm into the disk, melting the metal. An intense shock wave traveled through the disk, ripping away chunks of metal when it reached the rear surface (shown in figure). Photograph courtesy of Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico.



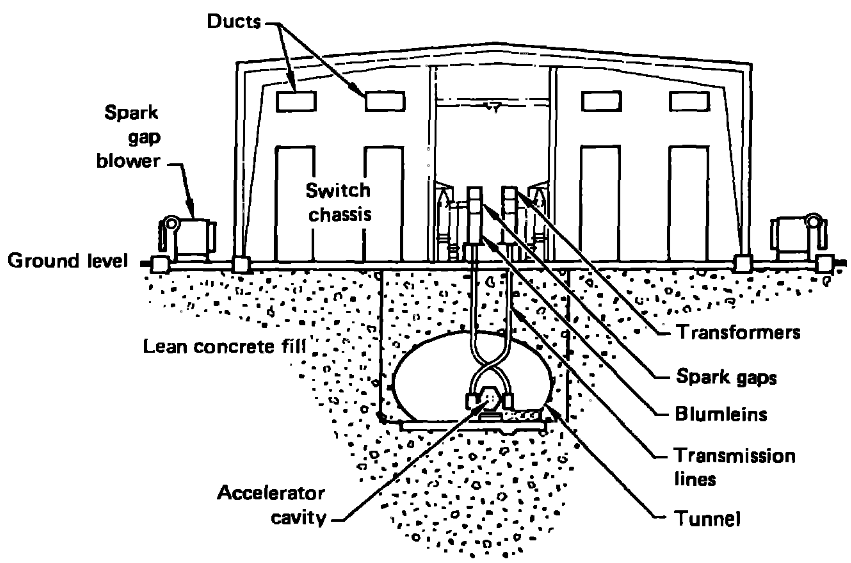


Figure 3 - Sketch of the ATA facility showing arrangement of major components: the pulsed-power network, the electron injector, the accelerator, and the shielded, gas-filled experimental tank. (Many of the vertical elements forming the pulsed-power network have been omitted for simplicity.) This whole assemblage will be 200 m long. The cross-section of the accelerator shows the end of one accelerator cavity, located in an underground tunnel, as well as the Blumleins connecting it to the pulsed-power transformers above ground.

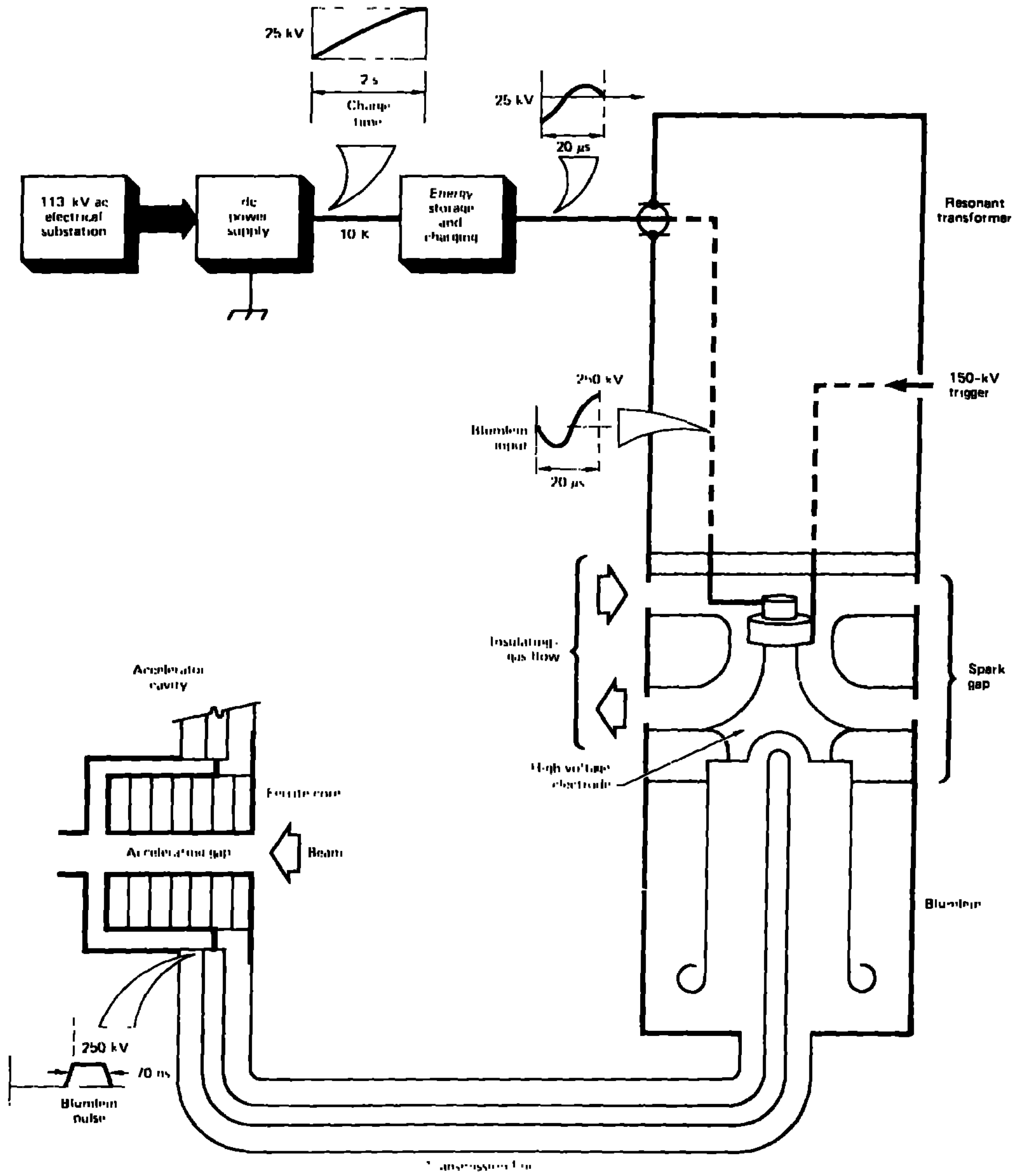


Figure 4 - Diagram of the ATA's pulsed-power-forming network. Pulsed electrical power for the accelerator units is provided by a pulse-forming network that converts ac power from a transformer substation into short, very high-voltage pulses. The key process in forming the pulse is the charging of a Blumlein transmission line (similar to the charging of a capacitor) over a relatively long period and the subsequent fast discharge of the Blumlein in 1/150 of the charging time.

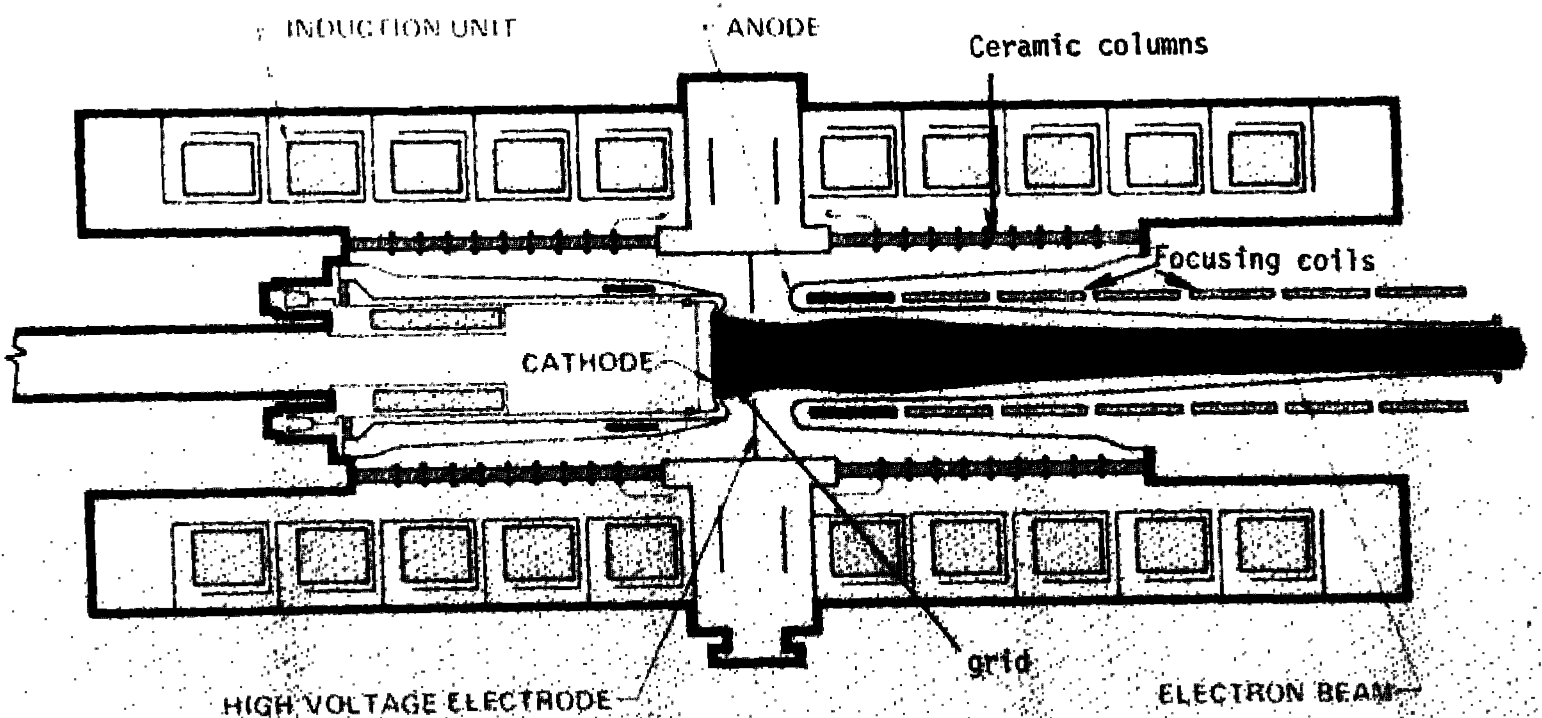


Figure 5 - A schematic drawing of the 2.5 MeV electron injector for the ATA. The 2.5 MV between the anode and cathode (provided by 10 induction accelerator units of 0.25 MV each, connected in series) extracts 10 kA from the large cathode. Note that the beam begins to spread soon after it enters the anode but that focusing coils quickly focus it to a smaller diameter before it is injected into the accelerator. The beam's spreading and focusing is drawn here according to precise calculations of actual beam behavior.

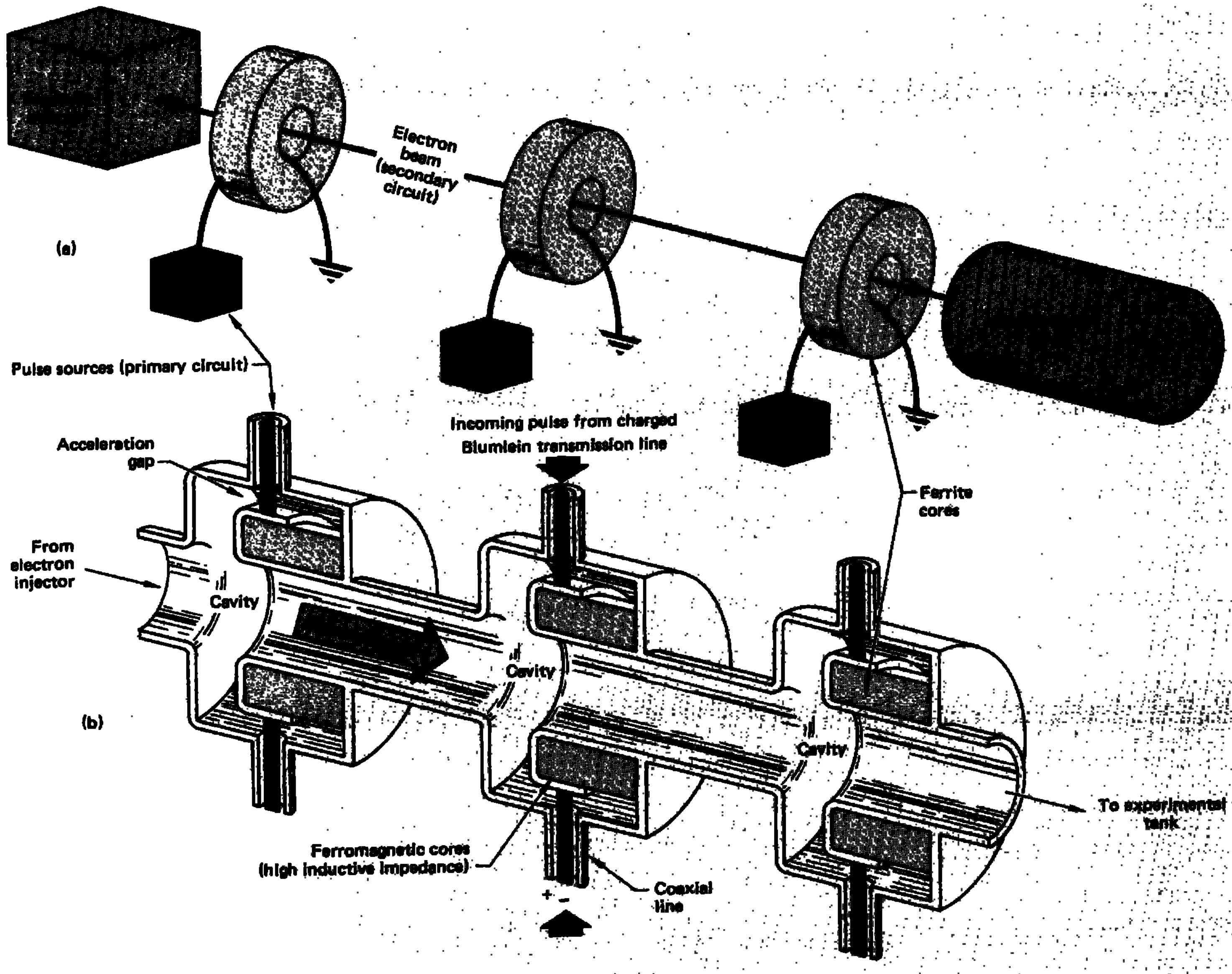


Figure 6 - Two diagrams of the accelerator modules in the ATA. (a) Generalized representation of the relationship of the two circuits in the accelerator, the electron beam and the pulsed power that drives it through the ferrite cores. (b) A more specific drawing (longitudinal section) of the accelerator module. This structure is essentially a long metal tube consisting of a series of chambers, or cavities, containing ferrite rings that prevent the current in the coaxial line from shorting. Blumlein transmission lines deliver a high-voltage pulse to each cavity just as one of the electron clusters that make up the beam reaches the cavity. The electron clusters thus pass from one cavity to the next, increasing in momentum each time, until they attain an energy of 50 MeV.

ATA EXPERIMENTAL FACILITY

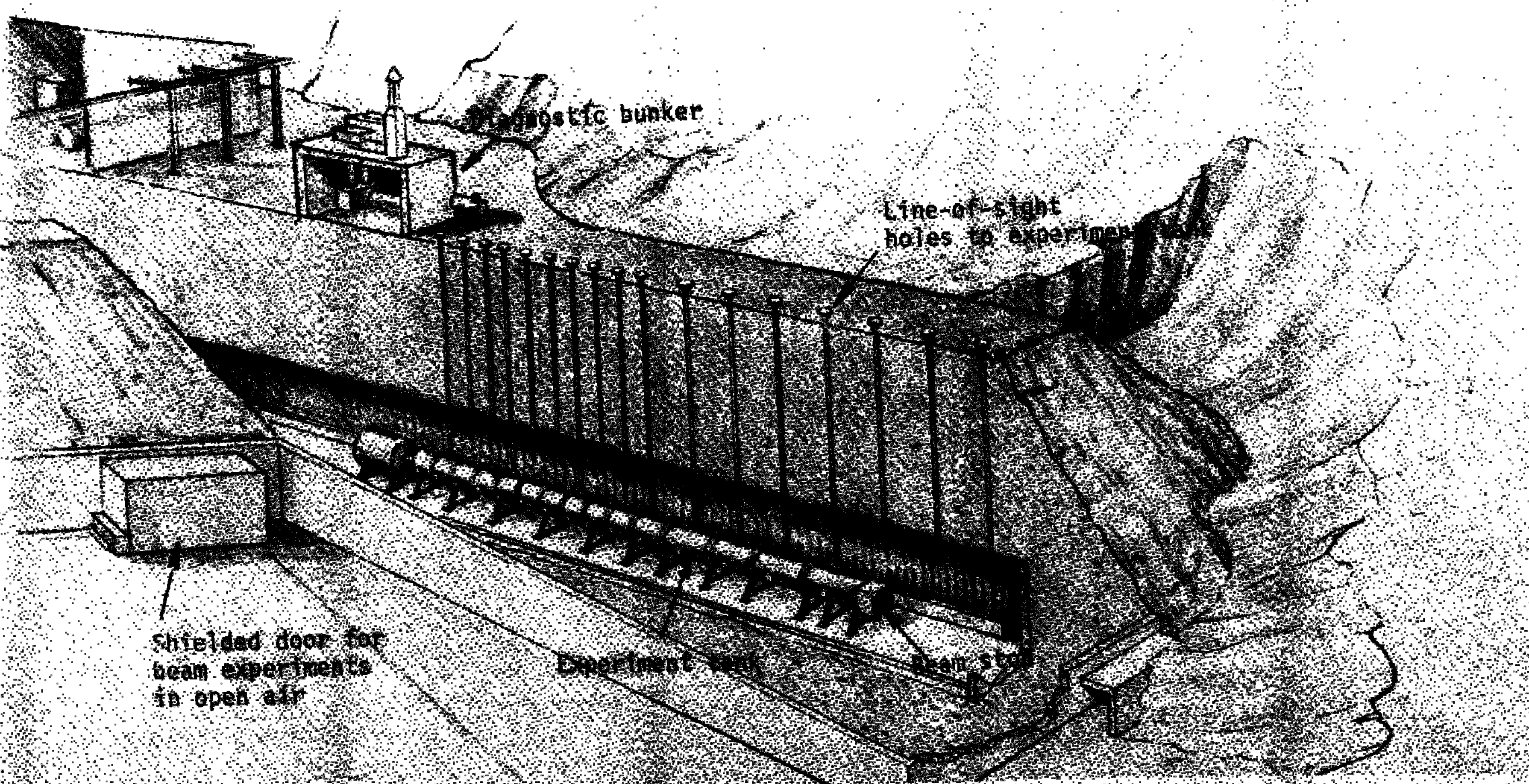


Figure 7 - The completed ATA facility will permit experiments on beam behavior both in a shielded gas tank and in open air. The artist's sketch shows the underground experiment tank into which the beam will be directed. The thick earth cover will absorb stray radiation, and the pipes from the ground surface down to the tunnel will allow access for diagnostic instruments. The instruments can be monitored from the shielded bunker above the tank. To the left of the tank, a door can be opened to allow the beam to be aimed into the atmosphere.